Land Use and Land Cover Characterization within Air Quality Management Decision Support Systems: Limitations and Opportunities

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Executive Summary

Air Quality Models (AQMs) are used to study atmospheric dynamics and chemistry that govern the transport and transformation of natural and man-made emissions. They play a central role in air quality management and are commonly used 1) to assess the impact of individual sources on air quality, deposition and visibility; 2) to demonstrate the effectiveness of emission control strategies aimed at achieving compliance with regulatory standards, and 3) to forecast air pollution events that might pose a health hazard for the general public, as well as sensitive groups (e.g., children, elderly). The National Aeronautics and Space Administration (NASA) Applied Sciences program requested the Marshall Space Flight Center (MSFC) to assess the feasibility and potential benefits of facilitating incorporation of NASA's remotely sensed Land Use/Land Cover (LULC) data within commonly used air quality and associated meteorological modeling systems. We identified two pollutant dispersion/meteorology models, one photochemical grid model, and two mesoscale meteorological models for a literature review. This was followed by a verbal and a written survey. This document summarizes our findings and provides recommendations.

The American Meteorological Society/EPA Regulatory Model (AERMOD), the California Puff model (CALPUFF), and Models-3 or the Community Multi-scale Air Quality Chemical Transport Model (CMAQ-CTM) are the most commonly used dispersion and photochemical air quality models in the United States. The meteorological fields required by these models can be obtained from a variety of techniques and models. While diagnostic meteorological models AERMET and CALMET are used to provide meteorological fields for AERMOD and CALPUFF respectively, dynamic data assimilating meteorological models such as MM5 and WRF are used to generate meteorological input data for CMAQ-CTM applications. Since the state of the land surface (chiefly its temperature and moisture) strongly affects the fluxes of heat and moisture within the boundary layer, specification of LULC is critically important for accurate meteorological and air quality modeling. Inaccurate LULC information often leads to very large errors in surface energy fluxes and thus errors in boundary layer states. This is especially true for high resolution modeling (i.e., less than 4-km) of heat and air pollution events that are characterized by the absence of synoptic-scale forcing.

Air quality and associated meteorological models predominantly use the 24-category USGS dataset. Various studies indicate that this dataset is deficient in its characterization of the urban/suburban landscape, and better characterization of land surface will lead to improvement in the performance of the modeling system, especially its ability to capture the behavior of the nocturnal boundary layer. This will lead to more accurate predictions of night-time pollutant concentrations and their vertical distribution.

We recommend that the following project/activities be undertaken:

1. Incorporation of MODerate-resolution Imaging Spectroradiometer (MODIS) and National Land Cover Dataset (NLCD) LULC datasets within MM5 and WRF modeling systems; (annual) simulations in retrospective as well as forecasting modes, at different grid resolutions over urban and regional domains followed by comprehensive model performance evaluation.

2. Dispersion model applications using meteorological fields simulated by MM5 and WRF that incorporate MODIS and NLCD datasets, to test their sensitivity to different LULC classification schemes.
3. A focus in future field campaigns on providing observational datasets for meteorological/air quality model performance evaluation in terms of near-surface mass and energy transport and chemical deposition; - processes that couple the atmospheric boundary layer with the underlying LULC.

Background

The National Aeronautics and Space Administration (NASA) Applied Sciences program requested the Marshall Space Flight Center (MSFC) to assess the feasibility and potential benefits of facilitating incorporation of NASA's remotely sensed Land use/Land cover (LULC) data within commonly used air quality and associated meteorological modeling systems. We identified two pollutant dispersion/meteorology models, one photochemical grid model, and two mesoscale meteorological models for a literature review. This was followed by a verbal and a written survey. Individuals associated with local, state and federal agencies and the private sector involved in development and application of these models were identified (Table 1). Individual conference calls were arranged via phone and/or email, followed-up with a brief questionnaire (Figure 1). This document summarizes our findings and provides recommendations.

Introduction

Air Quality Models (AQMs) have been developed to study atmospheric dynamics (processes such as advection, turbulent mixing, wet and dry deposition) and chemistry that govern the transport and transformation of natural and man-made emissions. Two types of AQMs are extensively used: (Lagrangian) dispersion models and (Eulerian) photochemical models. Dispersion models use mathematical formulations to characterize the atmospheric processes that disperse a pollutant emitted by a source. Using observations and/or simulated meteorological fields, dispersion models can predict concentrations at selected downwind receptor locations. They are commonly used to assess the impact of individual sources on air quality, deposition and visibility. Generally, these assessments are required to be made under various provisions of the Clean Air Act (CAA). More specifically, atmospheric modeling is required for demonstrating compliance with the National Ambient Air Quality Standards (NAAQS), New Source Review (NSR), and Prevention of Significant Deterioration (PSD) regulations. More recently, attempts have been made to use dispersion models for assessing the relative impacts of local sources on nearby monitoring stations that the more sophisticated atmospheric modeling systems are unable to resolve. Apart from state and local agencies and the private sector, federal agencies that routinely use these models include 1) the U.S. Environmental Protection Agency (USEPA); 2) the National Park Service (NPS), the U.S. Fish and Wildlife Service (USFWS), and the U.S. Forest Service (USFS).

Photochemical models simulate the transport and transformation of gas- and aerosol-phase species over the region of interest by solving the discretized form of the Advection-Diffusion Equation. They require spatially and temporally resolved initial conditions, boundary conditions and emissions as well as meteorological variables such as horizontal and vertical wind components, temperature, water vapor mixing ratio, cloud vapor and liquid water content, precipitation, solar actinic flux, sea-level pressure, boundary-layer depth, turbulence intensity, and surface fluxes for heat, moisture and momentum. The simulated air quality fields are routinely used to assess public exposure to atmospheric pollutants, visibility degradation, acid deposition, and for demonstrating effectiveness of emission control strategies aimed at future compliance with NAAQS. They are also used to forecast air pollution events that might pose a health hazard for the general public, as well as sensitive groups (e.g., children, elderly). State and local agencies routinely use the modeling results to issue health advisories.

The accuracy of meteorological fields for an air quality modeling application is of considerable importance. In addition to transport, meteorological variables play a major role in determining chemical reaction and mass emission rates, as well as the spatial and temporal distribution of emissions from anthropogenic and natural sources. Historically, meteorological fields for air quality applications have been simulated either by a diagnostic or dynamical data assimilating meteorological model. While a diagnostic meteorological model attempts to produce dynamically consistent meteorological fields though univariant or multivariant objective analysis of observations collected at discrete points in time and space, the dynamical data assimilating model utilizes observations while integrating the non-linear hydrodynamic equations of motion or their derivatives. Data assimilation within a dynamical model is the preferred approach for photochemical air quality modeling applications, since it prevents the accumulation of error over time (a severe problem in dynamical models) and provides high quality, high resolution meteorological fields for multi-day (monthly, seasonal and annual) urban-to-regional-scale simulations.

LULC inputs are a critical part of the meteorological modeling system. In the absence of synoptic-scale forcing, the role of the land surface is particularly important in driving boundary layer evolution and ultimately precipitation patterns. Inaccurate LULC information often leads to very large errors in surface energy fluxes and thus errors in boundary layer states. Within meteorological models, many land surface variables are commonly defined as a function of LULC via a 'lookup table'. Variables frequently specified in this way include leaf area index (LAI), fractional vegetation cover, canopy height, emissivity, albedo, surface roughness, rooting depth and parameters related to stomatal resistance. These vegetation-related variables exert significant control on the surface temperature energy balance and subsequently on boundary layer processes and states, most importantly moisture and temperature profiles. The lookup table approach assumes a one-to-one relationship between the surface variable and the LULC category, with no variability represented within a LULC category. In many model applications, seasonal or monthly parameter values are defined, providing an annual cycle of vegetation phenology. In some applications, satellite observations are used to define a subset of these variables, primarily albedo, LAI and fractional vegetation cover. This is a much preferred method due to more realistic spatial and temporal representation of the surface.

Air Quality Modeling Systems

Air quality models most commonly used in the United States for research and regulatory assessment are, 1) American Meteorological Society/EPA Regulatory Model (AERMOD); 2) the California Puff model (CALPUFF), and 3) Models-3 or the Community Multi-scale Air Quality Chemical Transport Model (CMAQ-CTM). A brief description of these models, the meteorological processors and the LULC datasets that they employ is followed by a discussion of potentially useful NASA LULC datasets. We conclude with a proposed research agenda and expected benefits.

AMS/EPA Regulatory Model (AERMOD)

AERMOD (Cimorelli et al. 2004; Perry et al. 2003) is a steady-state dispersion modeling system developed by U.S. EPA for estimating near-field (50-km or less) impacts from surface and elevated sources. In 2005, U.S. EPA notified AERMOD as the preferred dispersion model. In 2007, local, state and federal agencies expect to receive approximately 1600 AERMOD modeling applications for review.

The regulatory version of AERMOD comprises two input data processors; AERMET (USEPA, 2004) and AERMAP (USEPA, 2004). AERMET, the meteorological processor calculates and provides to AERMOD Planetary Boundary Layer (PBL) parameters such as Monin-Obukhov length, surface friction velocity, convective scaling velocity, surface roughness length, surface heat flux, and convective and mechanical mixed layer heights. AERMOD uses the computed PBL parameters to generate vertical profiles of needed meteorological variables. AERMET requires meteorological observations and LULC-related surface properties, preferably at the source location. Observations include morning upper air sounding, either a single surface measurement of wind speed, wind direction, temperature, and cloud cover, or two measurements of temperature (at 2 and 10 meter), together with a single measurement of solar radiation. Surface properties required by AERMET are surface roughness length, Bowen ratio, and albedo. Appropriate value of these variables as a function of eight LULC categories (Water, Deciduous Forest, Coniferous Forest, Swamp, Cultivated Land, Grassland, Urban, and Desert Shrub land), four seasons (Spring, Summer, Autumn, Winter) and surface moisture (Dry, Wet and average moisture) are provided in the AERMET user's manual (Tables 2 and 3) . The precise characteristics of the eight LULC categories, seasons and surface moisture conditions have not been defined in the manual. Generally, users specify these values based on LULC of the nearby (preferably within 3-km) National Weather Service (NWS) station. In the near-future, U.S EPA is expected to release AERSURFACE – another preprocessor to AERMOD that will suggest appropriate values for a specific modeling application.

The depth of the boundary layer and dispersion of pollutants is dependent upon fluxes of heat and momentum, which are in turn influenced by LULC-related surface characteristics (e.g., surface roughness, moisture and reflectivity). These influences become increasingly important at local scales. Accurate characterization of the surface, at or near the source location is thus of importance.

California Puff model (CALPUFF)

CALPUFF (Scire et al. 2000; 1990a; 1990b) is a multi-layer, multi-species, non-steady-state puff dispersion model recommended by U.S. EPA for assessing long-range transport of pollutants and on a case by case basis for near-field applications involving complex meteorological conditions. First developed by Earth Tech, Inc. in the late 1980's, the model is maintained by the Atmospheric Studies Group (ASG) of TRC Companies Inc. (http://www.src.com/index.htm). It is being extensively used by Regional Planning Organizations (RPOs) to satisfy regulatory requirements set forth by U.S. EPA under the Regional Haze Rule. This year, local, state and federal agencies expect to receive approximately 1000 CALPUFF model applications for review.

CALPUFF model applications generally utilize gridded meteorological fields generated by the California Meteorological model (CALMET) (Douglas and Kessler, 1988). A prognostic meteorological model, CALMET contains a diagnostic wind field generator that performs objective analysis of observations (generally recorded at the NWS), incorporates a parameterized treatment of slope flows, and accounts for kinematic and blocking effects of terrain. Also part of CALMET are two separate micrometeorological models for a more accurate characterization of atmospheric boundary layer over land and water. In essence, CALMET uses meteorological observations together with gridded elevation and surface properties to generate hourly meteorological fields. The most recent version of CALMET is capable of processing meteorological fields simulated by Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Meteorological model (MM5), National Center for Environmental Prediction (NCEP) Eta model, and the Regional Atmospheric Modeling System (RAMS).

Geophysical data required by CALMET includes elevation, LULC type, surface roughness length, albedo, Bowen ratio, soil heat flux, vegetation leaf area index and anthropogenic heat flux. The data are incorporated within CALMET through various processors, which determine the average surface elevation (Table 4), fractional and dominant land use, as well as the weighted surface parameters for each grid cell. They are capable of processing 52-category USGS LULC data (Table 5) in which land use code is defined at the center point of each cell which are spaced 200 (for U.S. only) or 900 m (global coverage) apart in both east-west and north-south direction.

CALMET is flexible enough to allow the user to specify LULC-dependent value for each surface parameter. It also allows the user to define new LULC categories by remapping the USGS LULC categories. For example, the USGS land use category system has seven types of urban or built-up land and these would be mapped to one land use category for urban or built-up land in CALMET, if using the 14-category LULC (Table 6).

<u>Community Multi-scale Air Quality Chemical Transport Model (CMAQ-CTM)</u>

CMAQ-CTM or Models-3 (Byun et al., 1999) is an air quality modeling system with state-of-the-science parameterizations of atmospheric processes affecting transport, transformation, and deposition of such pollutants as ozone, particulate matter, airborne toxics, mercury, and acidic and nutrient pollutant species. It is being extensively used for air quality forecasting and emission control strategy development. The model was developed under guidance of the Atmospheric Modeling Division of U.S. EPA based in Research Triangle Park, NC. It was first released to the public in 1998. Support from the U.S. EPA and active participation of the scientific community has facilitated its continued development. The CMAQ-CTM modeling system is currently being maintained by the Center for Environmental Modeling for Policy Development (CEMPD) (http://cf.unc.edu/cep/empd/index.cfm) at the University of North Carolina at Chapel Hill.

CMAQ is an Eulerian air quality model, and solves the discretized form of the Advection-Diffusion Equation. Meteorological fields for CMAQ are generally obtained from dynamical data assimilating meteorological models (also referred to as mesoscale models). A processor called MCIP (Meteorology Chemistry Interface Processor) (Otte, 2004) is used to create input files for CMAQ. Its main function is to read in meteorological fields simulated by a mesoscale model, compute dry deposition velocities and other variables that CMAQ needs but are not available from the meteorological model, and output data in Models-3 IOAPI format. Currently, MCIP is capable of processing meteorological fields simulated by PSU/NCAR MM5 and the Weather Research Forecast (WRF) model. A brief description of these models follows.

PSU/NCAR Mesoscale meteorological model (MM5)

The fifth-Generation PSU/NCAR (Dudhia et al., 2002; Grell et al., 1994) system (http://www.mmm.ucar.edu/mm5/) is the last in a series of models first developed at Penn State in the early 1970's (Anthes and Warner, 1978). Supported by NCAR since its inception, MM5 went through a significant amount of change aimed at broadening its usage. Its use in air quality model applications became common after incorporation of four-dimensional data-assimilation (FDDA) capability. While no further development of MM5 is planned at NCAR, it continues to be the most commonly used meteorological model for air quality applications.

MM5 requires a significant amount of geophysical data. These data are interpolated on a user-specified modeling grid through a special processor capable of handling different types of vegetation/LULC and soil dataset (Tables 7 to 18). The output file generated by the processor contains grid-cell average surface elevation, fractional and dominant LULC, fractional vegetation, and soil type. Physical parameters (e.g., albedo, moisture availability, emissivity, surface roughness length, thermal inertia) for each vegetation/LULC category are defined within the Land Surface Model (LSM). In an MM5 model run without LSM, the physical parameters are assigned with the help of a look-up table.

Meteorological/air quality modeling simulations over urban areas require an adequate representation of the urban land surface. This is especially true for air pollution events that are characterized by low synoptic scale forcing. The 24-category USGS LULC dataset (USGS, 1994) that is used in most meteorological modeling/air quality applications is deficient in its characterization of the urban/suburban landscape (Quattrochi et al., 2006; Byun et al., 2004). As a result, mesoscale models are unable to accurately capture the behavior of the nocturnal boundary layer, leading to significant errors in air quality predictions.

Weather Research Forecast Model (WRF)

The Weather Research and Forecasting (WRF) modeling system (Skamarock et al. 2005; 2007; NCAR, 2006) (http://www.wrf-model.org/index.php) is an advanced mesoscale numerical forecast and data assimilation system designed for broad use in both research and operations. The effort to develop WRF has been a collaborative partnership, principally among NCAR, NOAA (NCEP and

Forecast Systems Laboratory), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, Oklahoma University, and the Federal Aviation Administration (FAA).

The WRF modeling system includes 1) the WRF software framework; 2) two dynamic cores: Advanced Research WRF (ARW) and the Nonhydrostatic Mesoscale Model (NMM); 3) a standard physics interface to facilitate the interoperability of model physics, 4) 2-way interactive, moveable nesting that enables use in a wide range of applications from weather to climate; 5) a full range of data assimilation options, 6) a wide range of physics options, and 7) coupling of land surface and ocean models. Relevant to air quality is the WRF model coupled with chemistry (referred to as the WRF/Chem model). A meteorological model simulation (i.e., MM5 or WRF) followed by an air quality model (i.e., CMAQ) simulation means that chemical transformations in the atmosphere are “decoupled” from meteorological processes. This “off-line” approach to atmospheric modeling does not allow an accurate assessment of chemistry-meteorology feedbacks, such as the effect of aerosols on the radiation budget or their interaction with Cloud Condensation Nuclei (CCN). Accurate representation of these processes may be of significant importance, especially for air quality prediction systems.

The WRF Preprocessing System (WPS) (NCAR, 2006) (http://www.mmm.ucar.edu/wrf/users/wpsv2/wps.html) creates input files for real-world WRF simulation. It consists of three programs which define and interpolate the geographical (static) and meteorological (dynamic) data onto the modeling grid. Geographical data includes soil and LULC categories, terrain height, annual mean deep soil temperature, monthly vegetation fraction, monthly albedo, maximum snow albedo, and slope categories (Table 19). While most WRF applications employ the 24-category USGS data, WPS is flexible enough to allow incorporation of additional data sets. WRF uses a procedure very similar to the one employed by MM5 for assigning physical parameters for the modeling grid.

LULC Datasets of Interest

NASA, other government agencies, and the private industry offer a variety of remotely sensed data and LULC products that are relevant to air quality modeling. A brief description of LULC datasets of interest is provided below.

The NASA Earth Observing System (EOS) provides a variety of platforms and instruments that produce LULC products. The MODerate-resolution Imaging Spectroradiometer (MODIS) Land Cover Classification products contain multiple classification schemes describing land cover properties. The primary land cover scheme (type 1) identifies 17 classes of land cover defined by the International Geosphere-Biosphere Programme (IGBP) which include 11 natural vegetation classes, 3 developed land classes (one of which is a mosaic with natural vegetation), permanent snow or ice, barren or sparsely vegetated, and water. The MOD12 classification schemes are multitemporal classes describing land cover properties as observed during the year (12 months of input data). Successive production at quarterly intervals of this "annual" product creates new land cover maps with increasing accuracies as both classification techniques and the training site database mature. Additional Science Data Set layers for other classification schemes include the

University of Maryland modification of the IGBP scheme (Land Cover Type 2), the MODIS LAI/fPAR (Land Cover Type 3) scheme, the MODIS Net Primary Production (Land Cover Type 4) scheme, and the Plant Functional Types (PFT) (Land Cover Type 5) provided to support the Community Land Model (CLM) used in climate modeling. Land Cover Type 5 includes 12 classes, however only one is an urban class. Four forest and two crop classes are also provided. These data are provided on an annual basis at a 1-km resolution, which are attractive features for use in air quality modeling systems.

The MODIS Global Vegetation Phenology product (MOD12Q2) provides estimates of the timing of vegetation phenology at global scales. As such, MOD12Q2 identifies the vegetation growth, maturity, and senescence marking seasonal cycles. The product is produced twice per year using 24 months of data as input (i.e., the 12 months of interest, bracketed by six months on either side) at a 1-km resolution. The first production period highlights July through June, and the second run focuses on January through December. This production schedule accounts for hemispheric differences in the timing of growing seasons, and enables the product to catch 2 growth cycles if necessary. The 1-km resolution, timely updates, and seasonality features are characteristics that may be beneficial to air quality modeling systems.

The Enhanced Thematic Mapper Plus (ETM+) is a multispectral scanning radiometer that is carried on board the Landsat 7 satellite. The sensor has provided nearly continuous acquisitions since July 1999, with a 16-day repeat cycle. The spatial resolution is 30 m for five visible and one near-infrared bands. Resolution for the panchromatic band is 15 m, and the thermal infrared band is 60 m. The National Land Cover Data (NLCD) derived from the early to mid-1990s Landsat Thematic Mapper satellite data, is a 21-category land cover classification scheme applied consistently over the United States. The spatial resolution of the data is 30 m and mapped in the Albers Conic Equal Area projection, NAD 83. This data set consists of four urban/suburban classes. Because of its 30 m resolution, the NLCD data facilitate representation of sub-grid scale LULC variability within a typical grid cell (1-10 km) of a mesoscale model. Through this procedure, the effects of small urbanized areas (relative to the model grid size) can be incorporated in a mesoscale model. This dataset is currently being revised based on Landsat-ETM+ data collected from the early 2000's.

Other government datasets that either have been used or are potential candidates for use include Advanced Very High Resolution Radiometer (AVHRR) data, Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), and commercial remote sensing data products. The GIMMS (Global Inventory Modeling and Mapping Studies) data set is a normalized difference vegetation index (NDVI) product available for a 22 year period spanning from 1981 to 2003. The data set is derived from imagery obtained from the AVHRR instrument onboard the NOAA satellite series 7, 9, 11, 14, and 16. This is an NDVI dataset that has been calibrated and corrected for view geometry, volcanic aerosols, and other effects not related to vegetation change.

ASTER is one of five remote sensing devices on board the Terra satellite launched into Earth orbit by NASA in 1999. The instrument has been collecting data since February 2000. ASTER provides high-resolution images of the Earth in 14 different wavelengths of the electromagnetic spectrum, ranging from visible to thermal infrared. The resolution of images ranges between 15 to 90 m. ASTER data are used to create detailed maps of surface temperature of land, emissivity, reflectance, and elevation. There is no LULC product produced by the ASTER sensor. While raw data provides the spectral range to produce a LULC classification at 15-m spatial resolution, this process would not be practical to provide LULC data for use in an operational modeling system.

The Landsat Data Continuity Mission (LDCM) is the future of Landsat satellites. It will continue to obtain valuable data and imagery to be used in scientific research and application. The Landsat Program provides repetitive acquisition of high resolution multispectral data of the Earth's surface on a global basis. The data from the Landsat spacecraft constitute the longest record of the Earth's continental surfaces as seen from space. Continuation of these data ensure the availability of high resolution satellite data for air quality modeling purposes, including the data needed to provide continuing updates of the NLCD.

Very high resolution commercial satellite data are available for development of LULC datasets. These data can provide a 2-3 m spatial resolution in a spectral range of visible to near infrared bands. Black and white data at 61-72 cm resolution are also available. The cost of data acquisition and the effort required to make this data available for operational use is prohibitive. However, the datasets are useful for research and validation.

Summary and Discussion

Air Quality Models (AQMs) are an integral part of the current regulatory framework, and are likely to remain so in the foreseeable future. They are central to air quality management decisions, which can affect policies related to transportation, energy, industry, and public health. AQMs range in scientific rigor and sophistication. Their data requirements are also different. LULC data are an important input to diagnostic and prognostic meteorological models that are used to generate meteorological fields for air quality model applications. Accurate characterization of the land surface has the potential to improve the performance of the meteorological modeling system. Characteristics of an 'ideal' LULC dataset for meteorological modeling include:

- High temporal resolution - monthly or shorter
- Timely – available within 15 days after collection
- High spatial resolution - 1 km or smaller
- Category differentiation – a large number of classes (>30) including several classes each in the general categories of urban agricultural and forest.

Air quality modeling applications predominantly use meteorological fields simulated by a mesoscale models that employ the 24-category USGS LULC. Among the key inputs to CMAQ are the dry deposition velocities of gas and aerosol-phase species. These are computed within CMAQ meteorological preprocessor MCIP. Dry deposition is an important atmospheric process through which gases and particles are removed by surfaces in the ecosystem. Since atmospheric turbulence, the nature and type of surfaces, ambient concentrations, and chemical properties of depositing species largely control this process, accurate LULC characterization has the potential to improve the performance of the modeling system, thereby strengthening the regulatory process.

Recommendations

We recommend that the following project/activities be undertaken:

1. Incorporation of MODIS and NLCD LULC datasets within MM5 and WRF modeling systems; (annual) simulations in retrospective as well as forecasting modes, at different grid resolutions over urban and regional domains followed by comprehensive model performance evaluation.
2. Dispersion model applications using meteorological fields simulated by MM5 and WRF that incorporate MODIS and NLCD datasets, to test their sensitivity to different LULC classification schemes.
3. A focus in future field campaigns on providing observational datasets for meteorological/air quality model performance evaluation in terms of near-surface mass and energy transport and chemical deposition - processes that couple the atmospheric boundary layer with the underlying LULC.

The activities recommended are expected to provide the following benefits.

1. Improved characterization of the nocturnal boundary layer, leading to more accurate predictions of night-time pollutant concentrations and their vertical distribution.
2. MM5 or WRF were primarily developed for weather forecasting. Use of more accurate LULC data has the potential to improve the ability of these models to forecast heat and air pollution events at finer spatial scales. This would lead to improved exposure assessment and public health management.
3. High resolution LULC data can provide improved emission estimates, especially for source categories that are meteorology- or LULC-dependent (i.e., on-road mobile sources, biogenic emissions, natural emissions of mercury).
4. Dry deposition is an important airborne pollutant loss mechanism. Accurate characterization of LULC will improve dry deposition estimates and increase our confidence in Urban Heat Island (UHI) mitigation strategies that attempt to improve air quality through lower surface temperatures and increased vegetation.
5. While U.S. application of dispersion models can benefit from high resolution meteorological fields simulated by mesoscale model’s that utilize more accurate LULC characterization, investment in CALPUFF and AERMOD will provide substantial benefit to scientists and engineers engaged in AQM applications worldwide.

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Figure 1 Sample questionnaire

Survey on the use of NASA Land use/Land cover (LULC) data in Air Quality Model (AQM) applications

Jon Doe
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Question: Identify the dispersion model that you are most familiar with? (Yes, it can be more than one)

Question: Please identify a) the primary model developer, b) primary use of the model, c) model users, and c) total number of model applications in the US.

Question: What Land use/Land cover (LULC) dataset does the model currently use? Is it a critical input to the model? How frequently is it update? Is it available globally?

Question: Does the model currently allow use of other (data that is not part of the current modeling system) LULC data? Would the model require extensive software engineering to incorporate new LULC data?

Question: What potential benefits could be realized through the use of more detailed LULC data within the model?

Question: What would be the approximate duration and cost for this undertaking?

Table 1 Contact information of survey participants

Contact	Model
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Table 2 Albedo and surface roughness as a function of season and LULC as specified in AERMOD modeling system

ALBEDO OF GROUND COVERS BY LAND-USE AND SEASON

Land-Use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.12	0.10	0.14	0.20
Deciduous Forest	0.12	0.12	0.12	0.50
Coniferous Forest	0.12	0.12	0.12	0.35
Swamp	0.12	0.14	0.16	0.30
Cultivated Land	0.14	0.20	0.18	0.60
Grassland	0.18	0.18	0.20	0.60
Urban	0.14	0.16	0.18	0.35
Desert Shrubland	0.30	0.28	0.28	0.45

SURFACE ROUGHNESS LENGTH, IN METERS, BY LAND-USE AND SEASON

Land-Use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.0001	0.0001	0.0001	0.0001
Deciduous Forest	1.00	1.30	0.80	0.50
Coniferous Forest	1.30	1.30	1.30	1.30
Swamp	0.20	0.20	0.20	0.05
Cultivated Land	0.03	0.20	0.05	0.01
Grassland	0.05	0.10	0.01	0.001
Urban	1.00	1.00	1.00	1.00
Desert Shrubland	0.30	0.30	0.30	0.15

Table 3 Bowen ratio as a function of season, LULC and moisture as specified in AERMOD modeling system

DAYTIME BOWEN RATIO BY LAND USE AND SEASON
DRY CONDITIONS

Land-Use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.1	0.1	0.1	2.0
Deciduous Forest	1.5	0.6	2.0	2.0
Coniferous Forest	1.5	0.6	1.5	2.0
Swamp	0.2	0.2	0.2	2.0
Cultivated Land	1.0	1.5	2.0	2.0
Grassland	1.0	2.0	2.0	2.0
Urban	2.0	4.0	4.0	2.0
Desert Shrubland	5.0	6.0	10.0	10.0

DAYTIME BOWEN RATIO BY LAND-USE AND SEASON
AVERAGE MOISTURE CONDITIONS

Land-Use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.1	0.1	0.1	1.5
Deciduous Forest	0.7	0.3	1.0	1.5
Coniferous Forest	0.7	0.3	0.8	1.5
Swamp	0.1	0.1	0.1	1.5
Cultivated Land	0.3	0.5	0.7	1.5
Grassland	0.4	0.8	1.0	1.5
Urban	1.0	2.0	2.0	1.5
Desert Shrubland	3.0	4.0	6.0	6.0

DAYTIME BOWEN RATIO BY LAND-USE AND SEASON
WET CONDITIONS

Land-Use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.1	0.1	0.1	0.3
Deciduous Forest	0.3	0.2	0.4	0.5
Coniferous Forest	0.3	0.2	0.3	0.3
Swamp	0.1	0.1	0.1	0.5
Cultivated Land	0.2	0.3	0.4	0.5
Grassland	0.3	0.4	0.5	0.5
Urban	0.5	1.0	1.0	0.5
Desert Shrubland	1.0	1.5	2.0	2.0

Table 4 CALPUFF Terrain database

Database Type	Description	Source	File Format	Reference System	Spatial Resolution (m)
USGS90	1-deg DEM 3 arc-second data	USGS	ASCII	Geographic (lat/lon)	~90
USGS30	7.5 min USGS quadrangle	USGS	ASCII	UTM	30
3CD	1-deg DEM 3 arc-second data	Rocky Mtn Communications CD-ROM	Binary	Geographic (lat/lon)	~90
GTOPO30	30 second DEM 40° lon. by 50° lat. covering world	USGS	Binary	Geographic (lat/lon)	~900
ARM3	30 second data 4 N-S sheets covering U.S.	CALPUFF CD-ROM (available from NTIS)	ASCII	Geographic (lat/lon)	~900
DMDF	7.5 min Alberta DEM	Alberta Environ. Protection	ASCII	UTM	~100

Table 5 CALMET Land Use Categories based on the U.S. Geological Survey 52-category Land Use and Land Cover Classification System

	Level I		Level II
10	Urban or Built-up Land	11	Residential
		12	Commercial and Services
		13	Industrial
		14	Transportation, Communications and Utilities
		15	Industrial and Commercial Complexes
		16	Mixed Urban or Built-up Land
		17	Other Urban or Built-up Land
20	Agricultural Land — Unirrigated	21	Cropland and Pasture
		22	Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas
		23	Confined Feeding Operations
		24	Other Agricultural Land
−20	Agricultural Land — Irrigated	−21	Cropland and Pasture
		−22	Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas
		−23	Confined Feeding Operations
		−24	Other Agricultural Land
30	Rangeland	31	Herbaceous Rangeland
		32	Shrub and Brush Rangeland
		33	Mixed Rangeland
40	Forest Land	41	Deciduous Forest Land
		42	Evergreen Forest Land
		43	Mixed Forest Land
50	Water	51	Streams and Canals
		52	Lakes
		53	Reservoirs
		54	Bays and Estuaries
		55	Oceans and Seas
60	Wetland	61	Forested Wetland
		62	Nonforested Wetland
70	Barren Land	71	Dry Salt Flats
		72	Beaches
		73	Sandy Areas Other than Beaches
		74	Bare Exposed Rock
		75	Strip Mines, Quarries, and Gravel Pits
		76	Transitional Areas
		77	Mixed Barren Land
80	Tundra	81	Shrub and Brush Tundra
		82	Herbaceous Tundra
		83	Bare Ground
		84	Wet Tundra
		85	Mixed Tundra
90	Perennial Snow or Ice	91	Perennial Snowfields
		92	Glaciers

Note: Negative values indicate irrigated land use.

Table 6 Default CALMET Land Use Categories and Associated Geophysical Parameters Based on the U.S. Geological Survey 14-category Land Use Classification System

Land Use Type	Description	Surface Roughness (m)	Albedo	Bowen Ratio	Soil Heat Flux Parameter	Anthropogenic Heat Flux (W/m^2)	Leaf Area Index
10	Urban or Built-up Land	1.0	0.18	1.5	.25	0.0	0.2
20	Agricultural Land - Unirrigated	0.25	0.15	1.0	.15	0.0	3.0
-20*	Agricultural Land - Irrigated	0.25	0.15	0.5	.15	0.0	3.0
30	Rangeland	0.05	0.25	1.0	.15	0.0	0.5
40	Forest Land	1.0	0.10	1.0	.15	0.0	7.0
50	Water	0.001	0.10	0.0	1.0	0.0	0.0
51	Small Water Body	0.001	0.10	0.0	1.0	0.0	0.0
55	Large Water Body	0.001	0.10	0.0	1.0	0.0	0.0
60	Wetland	1.0	0.10	0.5	.25	0.0	2.0
61	Forested Wetland	1.0	0.1	0.5	0.25	0.0	2.0
62	Nonforested Wetland	0.2	0.1	0.1	0.25	0.0	1.0
70	Barren Land	0.05	0.30	1.0	.15	0.0	0.05
80	Tundra	.20	0.30	0.5	.15	0.0	0.0
90	Perennial Snow or Ice	.20	0.70	0.5	.15	0.0	0.0

Table 7 Terrain height data

Resolution	Data source*	Coverage	Size(bytes)
1 deg. (111.0 km)	USGS	Global	129,600
30 min. (55.0 km)	USGS	Global	518,400
10 min. (18.5 km)	USGS	Global	4,665,600
5 min. (9.25 km)	USGS	Global	18,662,400
2 min. (3.70 km)	USGS	Global	116,640,000
Tiled 30 sec. (0.925 km)**	GTOPO30 by U.S. Geological Survey's EROS Data Center in late 1996	Global (33 tiles: 40° lon. x 50° lat. or 60° lon. x 30° lat.)	57,600,000 or 51,840,000 for each of tiles
30 sec. (0.925 km)	USGS	Global***	1,866,240,000

Table 8 PSU/NCAR Land-use data

Resolution	Data source	Coverage	Size(bytes)
1 deg. (111.0 km)	PSU/NCAR	Global	842,400
30 min. (55.0 km)	PSU/NCAR	Global	3,369,600
10 min. (18.5 km)	PSU/NCAR	Global	30,326,400

Table 9 17-category SiB Vegetation data

Resolution	Data source	Coverage	Size(bytes)
1 deg. (111.0 km)	Simple Biosphere model	0°-90°N, 60°-180°W	183,600
30 min. (55.0 km)	Simple Biosphere model	0°-90°N, 60°-180°W	734,400
10 min. (18.5 km)	Simple Biosphere model	0°-90°N, 60°-180°W	6,609,600
5 min. (9.25 km)	Simple Biosphere model	0°-90°N, 60°-180°W	26,438,400
2 min. (3.70 km)	Simple Biosphere model	0°-90°N, 60°-180°W	165,240,000
30 sec. (0.925 km)	Simple Biosphere model	0°-90°N, 60°-180°W	155,520,000

Table 10 25-category USGS vegetation data

Resolution	Data source	Coverage	Size(bytes)
1 deg. (111.0 km)	USGS	Global	1,620,000
30 min. (55.0 km)	USGS	Global	6,480,000
10 min. (18.5 km)	USGS	Global	58,320,000
5 min. (9.25 km)	USGS	Global	233,280,000
2 min. (3.70 km)	USGS	Global	1,458,000,000
30 sec. (0.925 km)	USGS	Global	933,120,000

Table 11 SiB Land-Water Mask data

Resolution	Data source	Coverage	Size(bytes)
1 deg. (111.0 km)	SiB Vegetation	0°-90°N, 60°-180°W	10,800
30 min. (55.0 km)	SiB Vegetation	0°-90°N, 60°-180°W	43,200
10 min. (18.5 km)	SiB Vegetation	0°-90°N, 60°-180°W	388,800
5 min. (9.25 km)	SiB Vegetation	0°-90°N, 60°-180°W	1,555,200
2 min. (3.70 km)	SiB Vegetation	0°-90°N, 60°-180°W	9,720,000
30 sec. (0.925 km)	SiB Vegetation	0°-90°N, 60°-180°W	155,520,000

Table 12 USGS Land-Water Mask data

Resolution	Data source	Coverage	Size(bytes)
1 deg. (111.0 km)	USGS Vegetation	Global	64,800
30 min. (55.0 km)	USGS Vegetation	Global	259,200
10 min. (18.5 km)	USGS Vegetation	Global	2,332,800
5 min. (9.25 km)	USGS Vegetation	Global	9,331,200
2 min. (3.70 km)	USGS Vegetation	Global	58,320,000
30 sec. (0.925 km)	USGS Vegetation	Global	933,120,000

Table 13 Global 17-category Soil data

Resolution	Data source*	Coverage	Size(bytes)
1 deg. (111.0 km)	FAO+STATSGO	Global	1,101,600
30 min. (55.0 km)	FAO+STATSGO	Global	4,406,400
10 min. (18.5 km)	FAO+STATSGO	Global	39,657,600
5 min. (9.25 km)	FAO+STATSGO	Global	158,630,400
2 min. (3.70 km)	FAO+STATSGO	Global	991,440,000
30 sec. (0.925 km)	FAO+STATSGO	Global	933,120,000

Table 14 Global monthly vegetation fraction data

Resolution	Data source	Coverage*	Size(bytes)
10 min. (18.5 km)	AVHRR	Global	27,993,600

Table 15 Description of 13-category (PSU/NCAR) land-use categories and physical parameters for N.H. summer (15 April – 15 October) winter (15 October – 15 April)

Landuse Integer Identification	Landuse Description	Albedo(%)		Moisture Avail. (%)		Emissivity (% at 9 μ m)		Roughness Length (cm)		Thermal Inertia (cal cm^{-2} k^{-1} s$^{-1/2}$)	
		Sum	Win	Sum	Win	Sum	Win	Sum	Win	Sum	Win
1	Urban land	18	18	5	10	88	88	50	50	0.03	0.03
2	Agriculture	17	23	30	60	92	92	15	5	0.04	0.04
3	Range-grassland	19	23	15	30	92	92	12	10	0.03	0.04
4	Deciduous forest	16	17	30	60	93	93	50	50	0.04	0.05
5	Coniferous forest	12	12	30	60	95	95	50	50	0.04	0.05
6	Mixed forest and wet land	14	14	35	70	95	95	40	40	0.05	0.06
7	Water	8	8	100	100	98	98	.01	.01	0.06	0.06
8	Marsh or wet land	14	14	50	75	95	95	20	20	0.06	0.06
9	Desert	25	25	2	5	85	85	10	10	0.02	0.02
10	Tundra	15	70	50	90	92	92	10	10	0.05	0.05
11	Permanent ice	80	82	95	95	95	95	0.01	0.01	0.05	0.05
12	Tropical or sub tropical forest	12	12	50	50	95	95	50	50	0.05	0.05
13	Savannah	20	20	15	15	92	92	15	15	0.03	0.03

Table 16 Description of 17-category (SiB) vegetation categories and physical parameters for N.H. summer (15 April – 15 October) winter (15 October – 15 April)

Vegetation Integer Identification	Vegetation Description	Albedo(%)		Moisture Avail. (%)		Emissivity (% at 9 μ m)		Roughness Length (cm)		Thermal Inertia (cal cm^{-2} k^{-1} $s^{-1/2}$)	
		Sum	Win	Sum	Win	Sum	Win	Sum	Win	Sum	Win
1	Evergrn. Broadlf.	12	12	50	50	95	95	50	50	0.05	0.05
2	Broadlf, Decids.	16	17	30	60	93	93	50	50	0.04	0.05
3	Decids. Evergrn.	14	14	35	70	95	95	40	40	0.05	0.06
4	Evergrn. Needlf.	12	12	30	60	95	95	50	50	0.04	0.05
5	Decids. Needlf.	16	17	30	60	93	93	50	50	0.04	0.05
6	Grnd. Tree Shrb.	20	20	15	15	92	92	15	15	0.03	0.03
7	Ground only	19	23	15	30	92	92	12	10	0.03	0.04
8	Broadlf. Shrb.P.G.	19	23	15	30	92	92	12	10	0.03	0.04
9	Broadlf. Shrb.B.S.	19	23	15	30	92	92	12	10	0.03	0.04
10	Grndcvr. DT. Shrb	15	70	50	90	92	92	10	10	0.05	0.05
11	Bare Soil	25	25	2	5	85	85	10	10	0.02	0.02
12	Agricltr. or C3 Grs	17	23	30	60	92	92	15	5	0.04	0.04
13	Perst. Wetland	14	14	50	75	95	95	20	20	0.06	0.06
14	Dry Coast Cmplx	19	23	15	30	92	92	12	10	0.03	0.04
15	Water	8	8	100	100	98	98	.01	.01	0.06	0.06
16	Ice cap & Glacier	80	82	95	95	95	95	5	5	0.05	0.05
17	No data										

Table 17 Description of 25-category (USGS) vegetation categories and physical parameters for N.H. summer (15 April – 15 October) winter (15 October – 15 April)

Vegetation Integer Identification	Vegetation Description	Albedo(%)		Moisture Avail. (%)		Emissivity (% at 9 μ m)		Roughness Length (cm)		Thermal Inertia (cal cm^{-2} k^{-1} s$^{-1/2}$)	
		Sum	Win	Sum	Win	Sum	Win	Sum	Win	Sum	Win
1	Urban	15	15	10	10	88	88	80	80	0.03	0.03
2	Drylnd Crop. Past.	17	23	30	60	98.5	92	15	5	0.04	0.04
3	Irrg. Crop. Past.	18	23	50	50	98.5	92	15	5	0.04	0.04
4	Mix. Dry/Irrg.C.P.	18	23	25	50	98.5	92	15	5	0.04	0.04
5	Crop./Grs. Mosaic	18	23	25	40	99	92	14	5	0.04	0.04
6	Crop./Wood Mosc	16	20	35	60	98.5	93	20	20	0.04	0.04
7	Grassland	19	23	15	30	98.5	92	12	10	0.03	0.04
8	Shrubland	22	25	10	20	88	88	10	10	0.03	0.04
9	Mix Shrb./Grs.	20	24	15	25	90	90	11	10	0.03	0.04
10	Savanna	20	20	15	15	92	92	15	15	0.03	0.03
11	Decids. Broadlf.	16	17	30	60	93	93	50	50	0.04	0.05
12	Decids. Needlf.	14	15	30	60	94	93	50	50	0.04	0.05
13	Evergrn. Braodlf.	12	12	50	50	95	95	50	50	0.05	0.05
14	Evergrn. Needlf.	12	12	30	60	95	95	50	50	0.04	0.05
15	Mixed Forest	13	14	30	60	94	94	50	50	0.04	0.06
16	Water Bodies	8	8	100	100	98	98	.01	.01	0.06	0.06
17	Herb. Wetland	14	14	60	75	95	95	20	20	0.06	0.06
18	Wooded wetland	14	14	35	70	95	95	40	40	0.05	0.06
19	Bar. Sparse Veg.	25	25	2	5	85	85	10	10	0.02	0.02
20	Herb. Tundra	15	60	50	90	92	92	10	10	0.05	0.05
21	Wooden Tundra	15	50	50	90	93	93	30	30	0.05	0.05
22	Mixed Tundra	15	55	50	90	92	92	15	15	0.05	0.05
23	Bare Grnd. Tundra	25	70	2	95	85	95	10	5	0.02	0.05
24	Snow or Ice	55	70	95	95	95	95	5	5	0.05	0.05
25	No data										

Table 18 Description of 17-category Soil categories and physical parameters

Soil Integer Identification	Soil Description	Max moisture content	Reference soil moisture	Wilting point soil moisture	Air dry moist content limits	Saturation soil potential	Saturation Soil conductivity (10^{-6})	B parameter	Saturation soil diffusivity (10^{-6})	Soil diffu./ condu. coef.
1	Sand	0.339	0.236	0.010	0.010	0.069	1.07	2.79	0.608	- 0.472
2	Loamy Sand	0.421	0.283	0.028	0.028	0.036	14.10	4.26	5.14	- 1.044
3	Sandy Loam	0.434	0.312	0.047	0.047	0.141	5.23	4.74	8.05	- 0.569
4	Silt Loam	0.476	0.360	0.084	0.084	0.759	2.81	5.33	23.9	0.162
5	Silt	0.476	0.360	0.084	0.084	0.759	2.81	5.33	23.9	0.162
6	Loam	0.439	0.329	0.066	0.066	0.355	3.38	5.25	14.3	- 0.327
7	Sandy Clay Loam	0.404	0.314	0.067	0.067	0.135	4.45	6.66	9.90	- 1.491
8	Silty Clay Loam	0.464	0.387	0.120	0.120	0.617	2.04	8.72	23.7	- 1.118
9	Clay Loam	0.465	0.382	0.103	0.103	0.263	2.45	8.17	11.3	- 1.297
10	Sandy Clay	0.406	0.338	0.100	0.100	0.098	7.22	10.73	18.7	- 3.209
11	Silty Clay	0.468	0.404	0.126	0.126	0.324	1.34	10.39	9.64	- 1.916
12	Clay	0.468	0.412	0.138	0.138	0.468	0.974	11.55	11.2	- 2.138
13	Organic Materials	0.439	0.329	0.066	0.066	0.355	3.38	5.25	14.3	- 0.327
14	Water	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	Bedrock	0.200	0.108	0.006	0.006	0.069	141.0	2.79	136.0	- 1.111
16	Other	0.421	0.283	0.028	0.028	0.036	14.10	4.26	5.14	- 1.044
17	No data									

Table 19 WPS/WRF input datasets

Name	Description
albedo_ncep	Monthly climatological albedo at 0.15 degree resolution
greenfrac	Monthly green vegetation fraction from AVHRR sensors aboard NOAA's polar orbiting satellite at 0.15 degree resolution
islope	14-category slope index
landuse_10m, landuse_5m, landuse_2m, landuse_30s	24-category USGS LULC at 10, 5, 2 meter and 30 second resolution
maxsnowalb	Climatological maximum snow albedo at 0.15 degree resolution
soiltemp_1deg	Annual mean deep-layer soil temperature at 1 degree resolution
soiltype_bot_10m, soiltype_bot_5m, soiltype_bot_2m, soiltype_bot_30s, soiltype_top_10m, soiltype_top_5m, soiltype_top_2m, soiltype_top_30s	FAO 16-category data for top and bottom soil layers
topo_10m, topo_5m, topo_2m, topo_30s	USGS derived 30s topographical height data